OPTIMA: A Photon Counting High-Speed Photometer

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Abstract. OPTIMA is a small, versatile high-speed photometer which is primarily intended for time resolved observations of young high energy pulsars at optical wavelengths. The detector system consists of eight fiber fed photon counters based on avalanche photodiodes, a GPS timing receiver, an integrating CCD camera to ensure the correct pointing of the telescope and a computerized control unit. Since January 1999 OPTIMA proves its scientific potential by measuring a very detailed lightcurve of the Crab Pulsar as well as by observing cataclysmic variable stars on very short timescales.

In this article we describe the design of the detector system focussing on the photon counting units and the software control which correlates the detected photons with the GPS timing signal.

Keywords: high-speed photometer — photon counting — GPS timing — software — hardware

Abbreviations: OPTIMA – Optical Pulsar Timing Analyser APD – Avalanche Photodiode CCD – Charge Coupled Device GPS – Global Positioning System PMT – Photomultiplier Tube UTC – Universal Time Coordinated

1. Introduction

Considering pulsar detections throughout the electromagnetical spectrum from radio to γ-rays, the low number of indisputable identifications in the optical band is striking. Up to now the search for optical emissions modulated at the pulsars' rotational frequencies has only succeeded in five significant or at least suspected detections (Cocke et al. 1969, Wallace et al. 1977, Middleditch & Pennypacker 1985, Shearer et al. 1997, Shearer et al. 1998). Nevertheless the optical emission from the neutron star's surface and magnetosphere can provide important insights into the emission processes and thermal conditions of pulsars. In the magnetosphere it marks the onset of nonthermal high energy processes that extend to X- and γ-ray frequencies and, from the hot surface as the Rayleigh Jeans part of a thermal spectrum, it provides estimates on the size of the star and its equation of state. To gain more information on pulsar emission in this decisive wavelength range, the γ-ray group of the Max-Planck-Institut für extraterrestrische Physik decided in 1996 to build a new high-speed photometer, the Optical

Pulsar Timing Analyser (OPTIMA), which should be useable as a stand-alone guest instrument at various observatories.

Since January 1999, more than one year before its final completion in fall 2000, the OPTIMA detector system has been used at several international telescopes to fine-tune its operation and to acquire first scientific data. During this commissioning phase we observed amongst others the well known Crab pulsar to demonstrate the very high time resolution of a few microseconds and its long-term stability over more than three consecutive days (Straubmeier 2001).

With the completion of the high-speed photometer in fall 2000 the OPTIMA detector is now ready for scientific useage on a wide variety of astronomical sources displaying variations of the intensity of their optical signal on short timescales.

2. Principle of Operation

The operation of the OPTIMA high-speed photometer is based on photon-counting, recording the arrival-time of every detected photon with a precision of a few microseconds. As the visual flux from most known or suspected optical pulsars is very low, a direct frequency analysis or stroboscopic observation of the measured intensity is impractical and precludes the later use of slightly different pulsar ephemerides or the derivation of longer term variations. On the other hand the individual recorded photons allow the use of rotational periods derived from other wavelength bands at a later stage of offline data analysis. The acquired arrival-times, properly corrected to the solar system barycenter, can then be converted to rotational phases by folding and a phase-coherent lightcurve histogram can be derived. Nevertheless the recording of the unprocessed arrival-times during the observation enables us further to search for pulsations at unknown frequencies in sources with a sufficiently high flux-level and to measure occultations, outbursts or quasi-periodic oscillations of other targets, like compact binary systems.

3. Hardware Layout

In order to use OPTIMA as a guest instrument on various large observatories, a basic requirement on the design of the detector system was, that it should be easily adaptable to different telescope configurations. As a consequence OPTIMA is a completely autonomous system incorporating all optics, electronics and computers which are neccessary for

its operation, so that only minor optical and mechanical adjustments are required to match the focal scale of the used telescope. In the course of its development, OPTIMA has been used on the Cassegrain foci of the Mt. Stromlo 74inch, ESO/MPG/La Silla 2.2m, Skinakas/Crete 1.3m and primarily on the 3.5m telescope of the German-Spanish Observatory on Calar Alto, Spain.

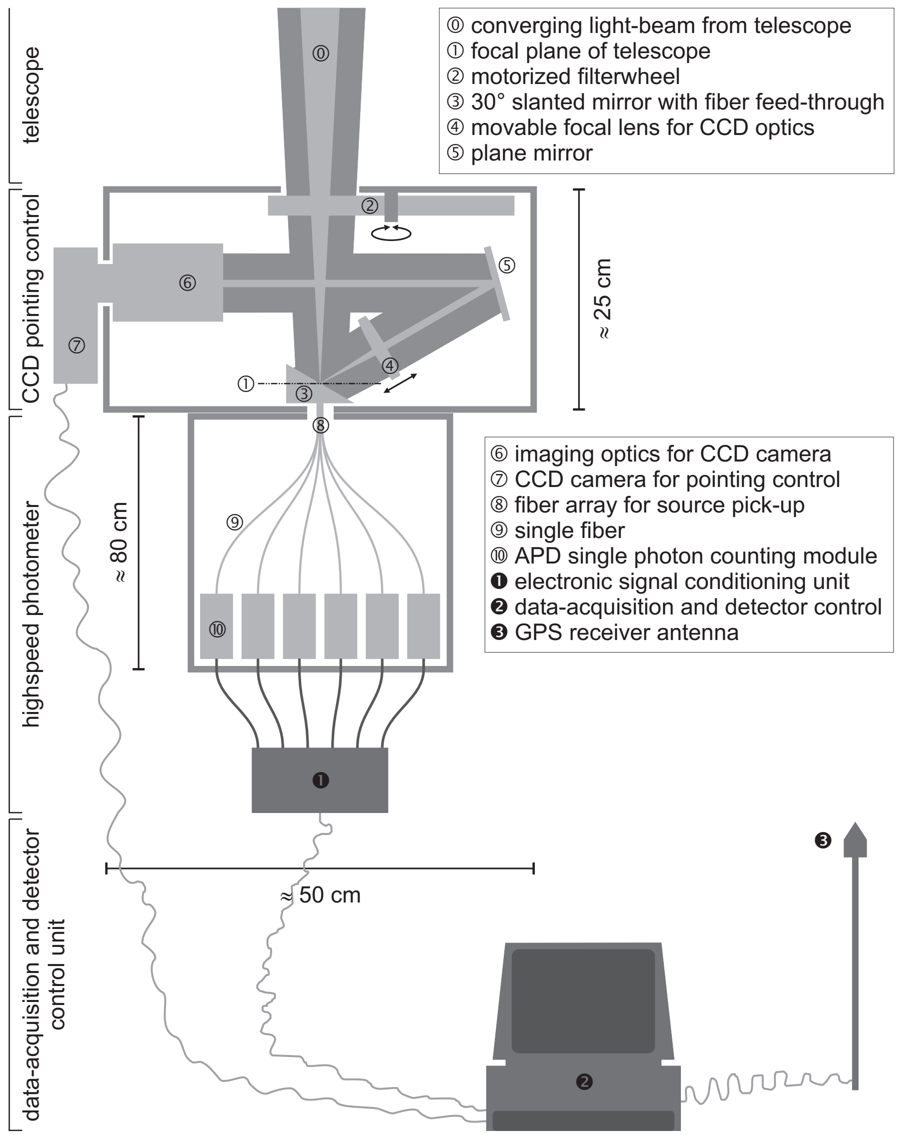

Figure 1. Simplified sketch of the hardware layout of OPTIMA

The detector hardware consists basically of four subsystems, which are sketched in figure 1 and will be discussed in turn in the next sections of this article:

- The high-speed APD counters
- The GPS receiver and high frequency time base
- Two personal computers for data-acquisition and detector control
- The integrating CCD camera for target acquisition and pointing verification

3.1. High-Speed Photometer

The basic purpose of a high-speed photometer is to record the radiation flux of a given source with a time resolution in the range of milliseconds or less. In the case of OPTIMA, which is primarily designed for studying the optical lightcurves of extremely faint pulsars ($m_V \approx 25^m$), the observed flux of the astronomical target lies considerably below the brightness of the night sky ($m_V \approx 22^m$ arcsec^{-2}) at even the best astronomical sites. To minimize the degradation of the source's signal due to the underlying atmospheric background, the flux of the target is isolated in the focal plane of the telescope by the use of an optical fiber pick-up which acts as a diaphragm. The signal to background ratio can then be maximized by matching the diameter of the fiber to the point spread function of the telescope and the expected seeing conditions (see section 3.1.1).

On a three meter class telescope during a typical pulsar observation in a moon-less night, the average detected photon-rate is about 1000 Hz, with more than 99% of it due to atmospheric background.

As the emission from optical pulsars is normally strongly polarized (Chen et al. 1996, Graham-Smith et al. 1996), a possible instrumental polarization may significantly affect the shape and dynamics of the observed lightcurve. To rule out such systematic effects in measurements with the OPTIMA high-speed photometer, a series of tests with unpolarized as well as linearly polarized calibration lamps have been performed in the laboratory. By equipping the motorized filterwheel of OPTIMA (item no. 2 in figure 1) with a continuously rotating polarization filter, the expected sinusoidal modulation of a polarized lightsource was clearly detected. When using an unpolarized input source no such modulation was found at the rotational frequency of the filterwheel.

This behaviour proves that no instrumental polarization is present and we therefore conclude that whithout additional filters the OPTIMA

high-speed photometer is insensitive to the polarization properties of the observed source.

3.1.1. *Fiber Pick-Up*

In order to minimize the contribution of the background sky and to maximize the signal to background ratio, the optical flux of the observed source and its underlying and adjacent sky region is picked up at the focal plane of the telescope by a hexagonal bundle of seven optical fibers (see figure 2). An additional single fiber is placed at a typical distance of about one arcminute from this bundle to monitor the sky brightness.

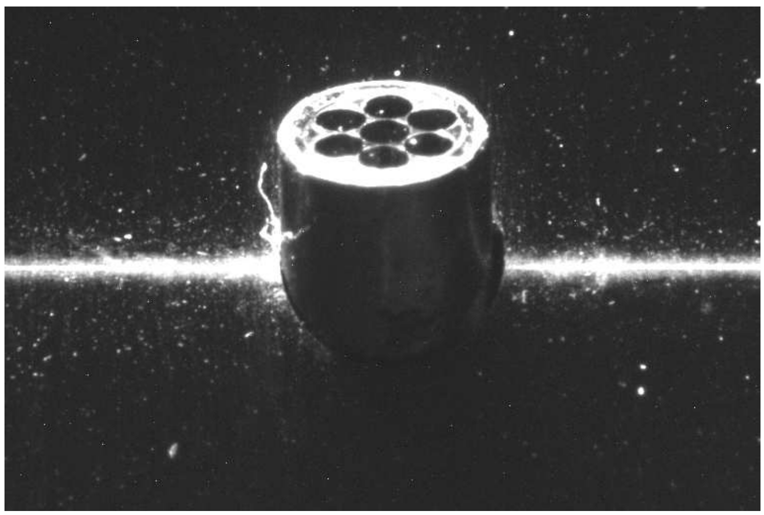

Figure 2. Hexagonal bundle of seven optical fibers fed through a hole in the slanted mirror at the focal plane of the telescope. For handling reasons the fibers are packed into a protective steel tube. The horizontal bright line is formed by an auxiliary mark on the mirror to ease focussing of the CCD optics.

By the use of exchangeable fiber tapers (optical fibers having different radii at both ends) it is possible to match the fiber diameter in the focal plane to the focal scale of the used telescope and the expected seeing conditions at the observing site. Usually a diameter corresponding to about two seeing discs is chosen. Having the target precisely positioned on the central fiber, this setup concentrates more than 98% of the flux of the observed object in this detector channel with the least possible amount of background light from the earth's atmosphere. In addition this setup leaves enough room to allow for small pointing variations being present at every telescope.

The recorded signals of the six fibers around the target and the more distant single fiber which monitor the sky background are used

to develop a time-dependent model of this background intensity at the location of the source. Thus it is possible to derive the time resolved flux of the source without contribution of the background radiation, which is a vital step for example to determine the extent of time invariant or only slowly variable emission of the observed object.

On the other end of each fiber the photons are fed to an APD detector, which provides the necessary conversion into electrical signals at a very high quantum efficiency and a very short response time.

3.1.2. *Avalanche Photodiodes*

In order to obtain a statistically significant measurement of faint sources within a limited observing time it is very important to convert the highest possible fraction of incoming photons into electronic countable signals. The crucial parameter for this conversion is the wavelength dependent quantum efficiency of the used photodetector. Up to now the standard detectors for recording single optical photons with time resolutions of a few microseconds are photomultiplier tubes (PMTs). PMTs deliver a high signal to noise ratio for the electrical pulse of a detected photon but the standard photo-cathodes have only a comparably low peak quantum efficieny of about 20% and a narrow wavelength range of sensitivity. Similar properties apply for the photo-cathodes of the Multi Anode Microchannel Array (MAMA) detectors used by Shearer et al., 1997, 1998. Cryogenic detectors based on superconducting tunnel junctions (Perryman et al. 1999, Rando et al. 2000) are also still limited to system efficiencies of around 30%, although they offer intrinsic spectral resolution. The cryogenic transition edge sensor developed by Romani et al., 1999, achieves only 2% system efficiency so far.

To overcome these limitations OPTIMA is based on state-of-the-art Avalanche Photodiodes (APDs). These new silicon based semiconductor devices offer a peak quantum efficiency of more than 60% and a wide band of sensitivity ranging from 400 to 1050 nanometers.

These two features result in a broadband gain of sensitivity of a factor of six in comparison to standard photomultiplier tubes. It is technically demanding to operate APDs as analog devices in a low noise and time-stable single photon counting configuration. The internal gain close to avalanche break-through critically depends on the temperature and the applied bias voltage. As a consequence the detectors and their preamplifiers have to be cooled to about -30°C and controlled to a fraction of a degree by a multistage Peltier system. The needed bias voltage in the range of several hundred volts needs to be adjusted and precisely maintained within a few millivolts.

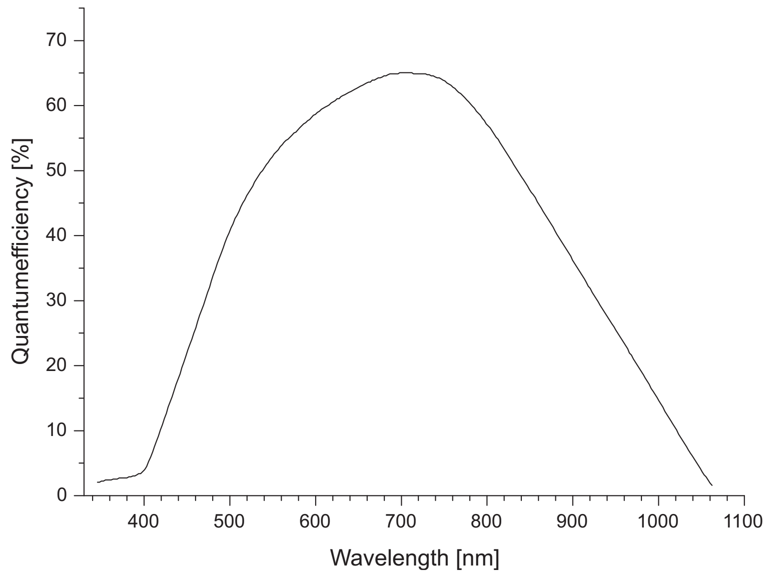

Figure 3. Quantum Efficieny of an APD Single Photon Counting Module based on data from the manufacturer, PerkinElmer Inc.

To speed up the completion of the OPTIMA detector system and to keep the detector electronics simple, we decided not to continue the initial development of a multi channel analog APD array for OPTIMA but to use eight units of the commercial available APD based Single Photon Counting Modules of PerkinElmer Inc. instead. These highly integrated devices operate in a Geiger counter mode where a photon initiated avalanche pulse is quenched by the instantaneous reduction of the bias voltage. The used APDs are of 0.2 mm diameter and are electrically cooled. The detector units selected for OPTIMA offer low dark count rates of typically less than 30 Hz, are insensitive to electromagnetic interference and are very reliable in operation. They can operate up to photon-rates of several 100 kHz before noticeable deadtime losses occur.

3.2. GPS Timing

To measure the lightcurves of pulsars with typical rotation periods from 33 ms (Crab) to 237 ms (Geminga) with a photon counting system like OPTIMA, the arrival-times of the individual detected photons have to be recorded with the precision of a few microseconds. This accuracy must be maintained continuously for the whole observing time spent on a selected target, which in the case of very faint sources might even extend over several consecutive nights. Otherwise the periodic signal of

a weak source would be smeared out during the process of folding the recorded arrival-times with the rotational period of the pulsar.

Keeping in mind that OPTIMA should be usable at different telescopes around the world, the signals of the global GPS satellites are the best available absolute time base. Using a special receiver which can process the clock pulses of up to six satellites simultaneously, it is possible to reach an absolute time accuracy of the one pulse per second GPS clock signal of better than two microseconds. Using this periodic signal to discipline a high frequency oscillator, a high resolution time base can be established with a maximum time deviation given by the error of the GPS clock signal. For OPTIMA we use a GPS based time and frequency processor of Datum Inc. which provides a continuous UTC time signal with a self adjusting absolute accuracy of better than two microseconds to the system bus of a personal computer as well as on external connectors.

3.3. Data-Acquisition

The most crucial task of the computer based data-acquisition unit is to correlate the electronic signals of the APD detector modules with the high resolution time base and thus assign UTC arrival-times to each detected photon. This association is done on hardware level to ensure a reliable operation even on a non realtime operating system and under high system load. The timing of the conversion cylces of the data-acquisition card is therefore done by the GPS based high frequency oscillator, so that the transfer of the APD detector signals to the computer system is running at a fixed rate.

As the precise starting time of each software triggered acquisition sequence is well known, the remaining job of the controling software is to count the number of conversion cycles since the start of the sequence and to store this sequential number together with an identifier of the respective detector channel for each detected photon. Based on the cycle number, the acquisition frequency and the absolute time of the start of the sequence the UTC arrival-time of every recorded photon can be restored during data analysis.

If one considers observing times of several nights, eight detector channels, an acquisition frequency of several 100 kHz and an atmospheric background photon-rate of about 1 kHz the total amount of data is quite formidable. However the chosen method of storing the arrival-time data poses quite acceptable demands on the required computer memory because all conversion cycles without any detected photon can be skipped and most of the stored data consists of small integer

numbers. Nevertheless one night of observation still produces several gigabytes of data.

3.4. CCD Positioning Camera

By the use of optical fibers only the flux of the targeted object and a small adjacent region of sky is transfered from the focal plane of the telescope to the APD high-speed counters. The light of the more extended region of surrounding sky (about 3-4 arcminutes in size) is reflected by a slanted mirror into a focal reducer and imaged by a ST-7 integrating CCD camera of the Santa Barbara Instrument Group. In conjunction with this CCD image the catalogued astronomical positions of several bright stellar objects in the vicinity of the target can be used to verify the acquisition of the fiber array and the correct pointing of the telescope. This ability to point the telescope using bright guide stars with known separations from the target makes it possible to position the high-speed photometer even on very weak sources, which themselves are too faint to be visible within a reasonable integration time.

With appropriate electrical connections to the telescope control system the OPTIMA CCD camera can also operate as a guiding system to ensures the long-term stable pointing of the telescope by automatically correcting small deviations. This possibility enables us to use OPTIMA at telescopes which do not provide a stationary stand-alone star-tracker for guest instruments.

4. Control Software

Most of the functions of the OPTIMA detector system are remotely controlled by software running on two personal computers located at the observers' room. From these two machines (one for the control and the data-acquisition of the high-speed photometer and one for the control of the integrating CCD camera) all observing parameters of OPTIMA can be monitored and changed interactively.

In contrast to the readout and image-processing software for the CCD camera, where a well standardized CCD command language is available and several commercial software products can be used, most of the required software for the operation of the high-speed photometer was newly developed by ourselves. The software includes operation modes for data-acquisition, setup and control of the APD detector modules and the GPS receiver as well as some low level data analysis procedures including a flexible data interface to export the pre-processed data to other scientific software packages. The analysis part

especially provides some fundamental tasks for pulsar research like the correction of the recorded local UTC arrival-times to the reference frame of the solar system barycenter, the calculation of phase-coherent intensity histograms based on externally supplied rotational parameters of the observed source, or a variety of frequency analysis tools for the search for pulsations at unknown periods.

The process of barycentering the recorded UTC arrival-times corrects the acquired data for timing shifts and Doppler effects due to the daily and annual motion of the earth and makes the individual measurements comparable between different epochs and observing sites. The possibility to use the known ephemerides of the source from observations in other wavelength bands allows the calculation of lightcurve histograms even of very faint objects, where the optical periodic signal is too weak to determine the frequency of pulsation with sufficient precision from the OPTIMA data alone.

5. First Light of the OPTIMA Detector on the Crab Pulsar

To start with the commissioning and fine tuning of the detector system as soon as possible, OPTIMA was designed to be already useable for first astronomical observations with a smaller number of detector channels than the final eight APDs. In late December 1999, when the assembly and lab testing of OPTIMA with two detector channels was successfully completed, we observed the bright Crab Pulsar (PSR B0531+21, $m_V = 16.6^m$) at the 3.5m telecope of the German-Spanish observatory on Calar Alto, Spain. Because of its relatively high visual brightness and high rotational frequency, this pulsar has been a favourite target for the demonstration of the respective capabilities of many optical high-speed photometers (Beskin et al. 1983, Eikenberry et al. 1997, Golden et al. 2000, Perryman et al. 1999, Romani et al. 1999). Considering the limiting properties of the system due to the small number of available detector channels and due to a not yet optimized set of optical fibers, the results of these short observations nevertheless give a striking impression of the performance and future potential of our new high-speed photometer.

Using the well known periodicity of the Crab Pulsar as one of the most precise clocks available and analysing the measured phase positions of the sharp main peak of the lightcurve on four consecutive nights, the absolute timing of OPTIMA proved to be accurate to better than 100 μsec over an observing time span of more than 80 hours. At the highest possible time resolution the analysis was limited by the low number of photons recorded from the source, which was observed for

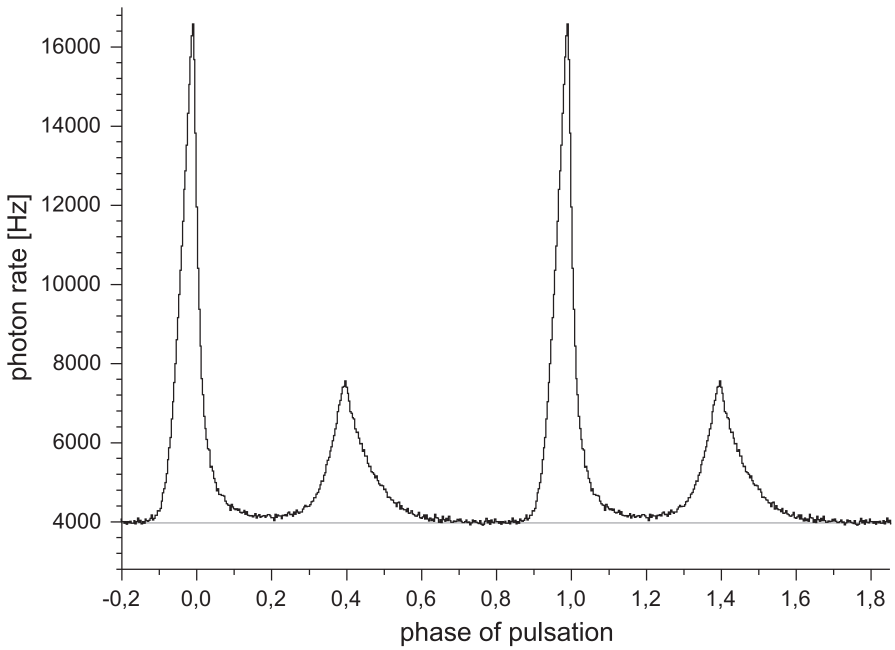

Figure 4. Lightcurve of the Crab Pulsar (PSR B0531+21) as measured with OPTIMA in December 1999 at the Calar Alto 3.5m telescope in a 10 minute exposure. The plotted numbers represent the absolute countrates of the detector, which are neither corrected for the contribution of the atmospheric background radiation nor for the intensity of the emission nebula surrounding and overlapping the pulsar. The horizontal line at approximately 4000 Hz shows the result of a linear fit to the phase interval of lowest intensity at $0.7729 \leq \varphi \leq 0.8446$. This level roughly identifies the flux of the nebula at the position of the pulsar (Percival et al. 1993)(Straubmeier 2001). At the epoch of this observation one rotational cycle of the pulsar equals 33.505115 msec and the size of the plotted phase intervals is approximately 112 μsec (300 bins per rotation). For clarity two consecutive cycles of pulsation are plotted.

only about 20 minutes during each night, resulting in a total exposure time of about 80 minutes. The given upper limit of the timing accuracy of OPTIMA is therefore expected to be improved by about one order of magnitude by a more extensive observation of this source, which is being planned for the near future.

5.1. Phase-Coherent Folding of Arrival-Times

In figure 4 we show the lightcurve of the Crab Pulsar as measured with OPTIMA in December 1999. For the calculation of this intensity histogram the recorded arrival-times of the detected photons have been corrected to the solar system barycenter and were folded with the rotational period of the source as published monthly by the Jodrell

Bank Radio Observatory (Lyne et al. 1992). With only two detector channels available it is not possible to isolate the optical flux of the pulsar from the contribution of the underlying spatially highly inhomogenous emission of the Crab Nebula and the night sky background. The plotted counting rates therefore represent the summed intensity of these components per phase interval. For clarity figure 4 shows two rotational cycles of the pulsar with one full rotation corresponding to 33.505115 msec. The zero point of the plotted phase index is defined by the arrival of the main radio pulse at the solar system barycenter.

A comparison of the basic characteristics of our measured lightcurve to the published data from the former high-speed photometer aboard the Hubble Space Telescope (Percival et al. 1993) shows that the OPTIMA detector system contributes no detectable timing noise or non-linear intensity response to the optical signal variation of the pulsar (Straubmeier 2001). The obtained lightcurve demonstrates that OPTIMA can resolve even large intensity variations down to a timescale of fractions of milliseconds and presumably even further when more observational data becomes available.

5.2. Frequency Analysis

For the detection of periodic signals with very sharp features covering only a small fraction of the full period the Z^2 test statistics of Buccheri (Buccheri et al. 1983) proved to be very sensitive. In addition to the fundamental mode of oscillation this test considers an adjustable number of higher harmonics as well and therefore reaches a high sensitivity for non-sinusoidal signals. Regarding the overall shape of the lightcurve of the Crab Pulsar with a phase extent of pulsed emission of approximately 20% we chose a Z^2_{10} test, which includes the fundamental mode and its first nine harmonics.

Figure 5 shows the result of a high resolution narrow band frequency analysis of a ten minute OPTIMA dataset of the Crab Pulsar taken in December 1999. Due to the relatively high brightness of the source with $m_V = 16.6^m$ the intensity of the detected signal is immense and the precision of the determination of the rotational frequency of the underlying neutron star is striking. In figure 5 the plotted increment in frequency between two consecutive calculated values of the power spectrum is $5{\cdot}10^{-5}$ Hz (solid line) and the numerical parameters of the overlaid gaussian fit (dotted line) show that the frequency of pulsation at the observed epoch can be determined with a very small error of approximately $5{\cdot}10^{-7}$ Hz (Straubmeier 2001).

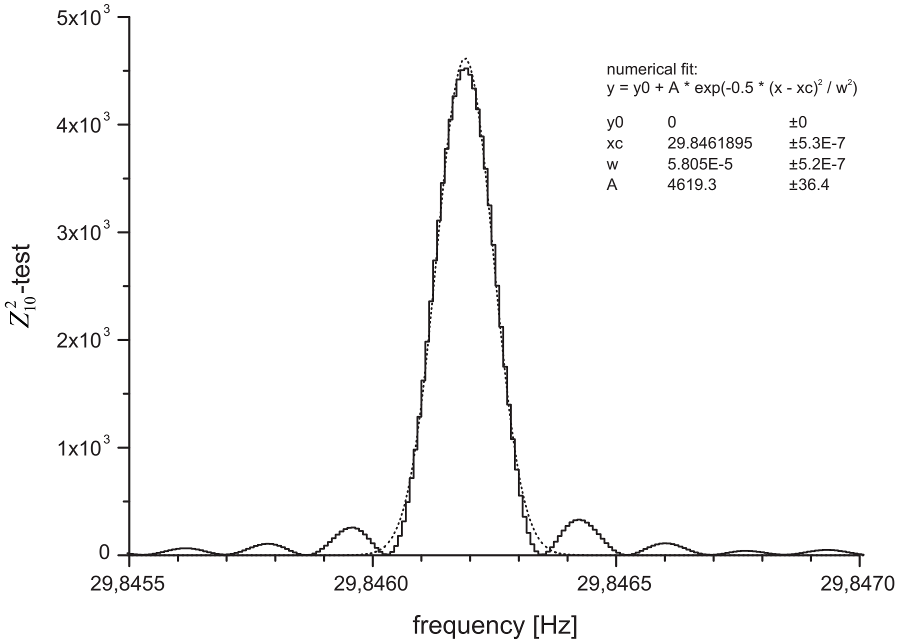

Figure 5. Frequency spectrum of the Crab Pulsar in December 1999. The plotted intensities are the results of a Z^2_{10} test considering the fundamental mode of pulsation and its first nine harmonics.

6. Summary and Future Perspective

With its first light observation of the Crab Pulsar in Dezember 1999 the new optical high-speed photometer OPTIMA of the γ-ray group of the Max-Planck-Institut für extraterrestrische Physik proved its scientific potential at recording the periodic intensity variations of the Crab Pulsar with very high time resolution.

In fall 2000 the number of operational APD detectors modules reached the proposed number of eight channels and OPTIMA is fully configured. Now the possibility for a precise correction of the measured flux at the position of the target for the contributions of the atmospheric background and other nearby astronomical objects is available. Analysing the lightcurves of periodic sources like pulsars this correction is needed to calculate the intensity of a possible constant emission. Besides of that, the detector system can now determine the time resolved flux of any source with full correction of the sky background. This enables us to use OPTIMA even on aperiodic targets or objects with long time constants. As the slow (order of minutes) but always present changes of the atmospheric brightness can now be well separated from the signal of the source without the necessity of folding the recorded

arrival-times with a short time constant, OPTIMA can now be used on all astronomical objects displaying fast intensity fluctuations, flares, eclipses or quasi-periodic oscillations.

To demonstrate the feasibility of a precise background correction and the ability to study a long periodic source with OPTIMA, we recorded several orbits of the eclipsing cataclysmic binary system HU Aquarii in summer 2000 from the 1.3m telescope on Mt. Skinakas, Crete. At this time already five APD channels of the high-speed photometer were available and it was possible to successfully correct the flux of the binary system for the intensity of the atmospheric background with great accuracy.

A discussion of the OPTIMA results obtained on HU Aquarii as well as a very detailed analysis of our observation of the Crab Pulsar are presented in the PhD thesis of C. Straubmeier (Straubmeier 2001) and will be published in scientific journals in the near future.

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